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QSP Mode Characteristics of 3rd Generation ASP Powered Er:YAG Dental Lasers

Nejc Lukac[1], Matjaz Lukac[2], Matija Jezersek[1]
[1] University of Ljubljana, Faculty of Mechanical Engineering, Askerceva 6, 1000 Ljubljana, Slovenia
[2] Josef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia

ABSTRACT

One of the key factors that determine the regime and efficacy of Erbium laser ablation of dental tissues is the temporal shape of the laser pulse intensity. Temporal shaping of Erbium laser pulses has been until recently limited by the pulse forming technologies utilized to pump Erbium lasers. This has changed with the introduction of ASP (Adaptive Structured Pulse) pumping technology, which allows arbitrary shaping of the temporal envelope of laser pulses. Utilizing this 3rd generation ASP technology, it is now possible to adapt the temporal structure of laser pulses to the bio-photonic dynamics of laser-tissue interaction.

In this paper it is shown how the Quantum Square Pulse (QSP) modality, powered by the latest ASP technology, has enabled the simultaneous optimization of all three most-critical requirements for minimally invasive laser dentistry: fast cutting, minimal heat deposition and minimal vibration.

Key words: Er:YAG, laser dentistry, QSP mode, ablation efficacy, enamel, hard dental tissue, ASP, Adaptive Structured Pulse.

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I. INTRODUCTION

The Erbium (Er:YAG or Er,Cr:YSGG) laser is the laser of choice for effective, precise and minimally invasive ablation of hard and soft dental tissues [1]. Of all infrared laser wavelengths, the erbium laser wavelength of approximately 3 μm has the highest absorption in water and is thus optimal for the ablation of dental tissues.

In order to perform minimally invasive medicine, it is important to optimize an Erbium laser's parameters such that the laser cutting is fast, the cuts are sharp and precise, the procedure is quiet and with minimal vibrations imposed on the treated tissue, and the amount of residual heat that remains in the tissue following the Erbium laser irradiation is minimal. However, these requirements are to a certain extent contradictory, as parameters which may be optimal for, for example, achieving the fastest ablation, may not be optimal when minimal vibration and noise are required.

Depending on the laser pulse intensity (in W/cm^2) there are four ablation regimes [3]. At high intensities, the speed of ablation is faster than the diffusion of heat into the tissue, with all of the energy used up for "cold ablation". With decreasing intensity, the thermally influenced layer of tissue becomes thicker, the thermal effects become more pronounced and the ablation efficacy is considerably reduced ("warm" and at even lower intensities "hot ablation"). And at intensities below the ablation threshold there is "no ablation", consequently, all the energy is released in the form of heat.

Therefore, short pulses are, due to their high intensities, most suitable for achieving high ablation speeds [3]. However, shorter laser pulses produce higher frequency tissue vibrations [4] and therefore cause more discomfort to patients [5].

Similarly, when undesirable interaction of the laser beam with the debris cloud is considered, the effects of debris screening are less pronounced at longer pulse durations [6]. At short pulse durations, the incoming laser beam gets strongly absorbed in the dense debris cloud which forms above the irradiated area, resulting in a reduced ablation rate. Cuts are also less precise since the scattering effect caused by the cloud leads to spreading of the laser beam. And finally, as it falls back to the tissue surface the laser-re-heated debris cloud is expected to contribute to additional heating of the tissue, and consequently to additional residual heat deposition [7, 10].

When it comes to temporal shaping of the laser pulse intensity, there are currently three pulse-forming technologies that are being utilized to pump erbium dental lasers: Pulse Forming Network (PFN), Variable

Square Pulse (VSP) and most recently the Adaptive Structured Pulse (ASP) technology.

a) Conventional Pulse Forming Network (PFN) technology

Erbium lasers have traditionally employed a conventional Pulse Forming Network (PFN) technology to energize their flashlamps with high-energy light pulses [8]. Pulses created by single-PFNs are characterized by a typical temporal bell shape with a long declining tail (see Fig. 1a), and have a fixed pulse duration which is determined by the hardware component values of the PFN. Due to the varying instant intensity, the ablation modality of PFN-generated pulses shifts during a pulse from warm in the beginning of the pulse to cold at the peak of the pulse and again to warm and even hot towards the end of the pulse.

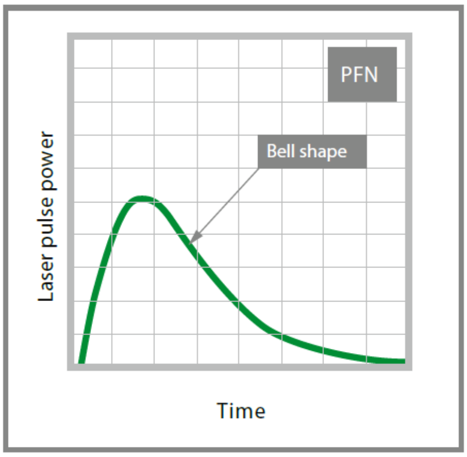
b) 2nd generation Variable Square Pulse (VSP) technology

With classical tools, such as burrs or scalpels, the interaction with the patient's tissue is guided mainly through tactile pressure on the dentist's hand. A laser dentist, however, does not rely on tactile feedback but can easily optimize the speed, finesse and depth of any treatment at the touch of a button, provided that the underlying technology can deliver the necessary power and flexibility. Er:YAG laser technology has advanced considerably with the development of Fotona's VSP (Variable Square Pulse) technology [8, 9], a flashlamp pumping solution that provides nearly square-shaped laser pulses that are adjustable over a wide range of pulse durations (Fig. 1b). This enables a significantly wider range of treatment protocols as well as greater precision and control. Due to the constant intensity of VSP pulses, the ablation modality does not uncontrollably shift during a pulse among hot, warm and cold ablation regimes as is the case with first generation PFN pulses [3].

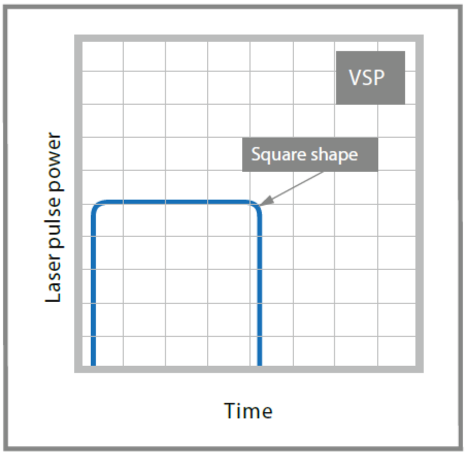
c) 3rd generation Adaptive Structured Pulse (ASP) technology

The latest Fotona ASP (Adaptive Structured Pulse) technology represents the next revolutionary step forward in the medical laser industry. ASP is a powerful technology that allows for shaping of the temporal envelope of laser pulses in ways that may be more advantageous, for instance, to go from a square pulse shape to something more complex (See Fig. 1c). Alternatively, individual pulses in a pulse-train can be broken up into multi-pulse burst sequences where each pulse is individually shaped in a different way.

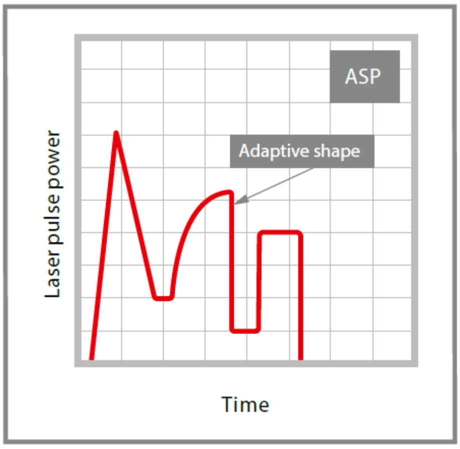
This third generation technology thus combines the large range of pulse duration modes of Fotona's VSP technology with the revolutionary capability of ASP technology to adapt the temporal structure of laser pulses to the bio-photonic dynamics of laser-tissue interaction.



a) Conventional PFN Technology



b) 2nd generation VSP technology



c) 3rd generation ASP technology

Fig. 1: Three types of Er:YAG laser pulse-forming technologies. The latest ASP (Adaptive Structured Pulse) technology allows for arbitrary shaping of the temporal envelope of laser pulses.

The ASP technology allows for completely new laser treatment modalities. In addition, with ASP, the characteristics of current pulse modalities can be optimized and adopted to what is required by the laser-tissue interaction dynamics.

Recently, a special QSP (Quantum Square Pulse) modality has been proposed with a goal to reduce the undesirable residual side effects of Erbium laser beam scattering and absorption in the debris cloud [7]. The QSP mode functions by breaking a longer pulse into a multi-pulse burst sequence to enable the delivery of laser energy with the efficacy of short-duration pulses, without sacrificing the precision and minimal vibration provided by long-duration pulses. Ablation measurements in dental enamel have subsequently demonstrated that as a result of the reduced undesirable effects of laser-debris interaction, the use of the QSP mode results in sharper cuts and higher ablation efficacy in enamel [7].

The 3rd generation ASP technology has enabled the QSP modality to be further improved by individually shaping each pulse "quanta" within the QSP pulse in order to optimally adapt the temporal pulse shape to the dynamics of laser-tissue interaction. The improved characteristics of the Quantum Square Pulse (QSP) Er:YAG laser modality, as generated by the ASP technology, have been recently demonstrated by a study that compared the performance of QSP modality to other Er:YAG and Er,Cr:YSGG dental laser modalities [10]. The ASP-generated QSP modality of the Fotona LightWalker dental laser was found to exhibit the highest ablation drilling efficacy with the lowest level of vibration and heat deposition.

In the above study [10], the drilling efficacy was determined by measuring the depth and diameter of ablated cavities. Since, cavities are not cylindrically shaped, this experimental data was not used to calculate the actual cavity volumes. However, in another recent study [11], an approximate experimental relationship was found between the volume, depth and diameter of ablated cavities in enamel. In this paper, we use this experimental relationship between the volume, depth and diameter of ablated cavities to calculate the ablated cavity volumes from the data reported in [10]. This allows us to obtain the ablation efficacy (defined as ablated volume per laser pulse energy) for the ASP-generated QSP modality and to compare it with the efficacy of other Erbium laser modes.

II. MATERIALS AND METHODS

In [10], the Er:YAG system used was an ASP-powered LightWalker AT (manufactured by Fotona), and the Er,Cr:YSGG laser was a WaterLase iPlus (manufactured by Biolase). Both lasers were fitted with the appropriate non-contact handpieces (Fotona H02 handpiece, and Biolase Turbo handpiece with MX11 tip). The lasers were operated in the following pulse modes and durations: a) Er:YAG laser in standard SSP (90 μsec), MSP (130 μsec) and SP (220 μsec) and in the new ASP/QSP mode; and b) Er,Cr:YSGG laser in a standard H pulse (400 μsec) duration mode. The above pulse durations represent the measured times during which 90% of the cumulative laser pulse energy was delivered to a target.

Experiments relevant to this paper were carried out under two conditions: a) "Dry" conditions where after the tooth has been taken out of the saline solution, no external water was added to the tooth during the ablation experiment; and b) with a "Hydration" experimental set-up which was designed to prevent, at least to a certain extent, the desiccation of the irradiated tooth surface. This was accomplished by re-hydrating the ablation area following each laser pulse with an external water spray. An optical microscope technique was used to measure the depths and external diameters of the ablated cavities. An interferometric setup based on a Fizeau configuration was implemented for measuring the vibration amplitudes of the tooth during the laser drilling.

For further details on the experimental conditions, refer to [10].

To calculate the volumes (V) of ablated holes from the published cavity depths (L) and diameters (d) as measured on the tooth surface, the following equation was used [11]:

$$V = 0.4\left(\frac{L\pi d^2}{4}\right)^2 + 0.3\left(\frac{L\pi d^2}{4}\right) \qquad (1)$$

III. RESULTS

Figure 2 shows the calculated dependence of ablated volume in enamel on the cumulatively delivered laser energy as obtained using Eq. 1 and the data presented in Fig. 5 of [10].

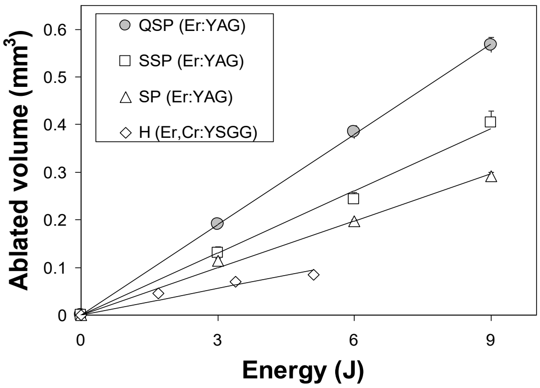


Fig. 2: Ablation volumes in enamel under "hydration" conditions for different Erbium laser modes as obtained using Eq. 1 and the data presented in [10, Fig. 5]. QSP, SSP and SP are Fotona LightWalker's Er:YAG laser modes, and H is Biolase iPlus's Er,Cr:YSGG laser mode.

IV. DISCUSSION

Optimization of Erbium laser performance for minimally invasive medicine may present a significant challenge as various requirements may oppose each other, with certain laser parameters being optimal for one requirement but sub-optimal for another requirement. This applies particularly when laser pulses with standard PFN or VSP shapes are being used.

This challenge has been overcome by the latest ASP (Adaptive Structured Pulse) technology, which allows for temporal adaptive structuring of laser pulses. An example of such adaptive structuring is the QSP (Quantum Square Pulse) temporally shaped pulse modality that results in an optimal Er:YAG laser performance with regard to all three basic requirements in dental tissue ablation: fast ablation (see Fig. 3), minimal heat deposition (see Fig. 4) and minimal vibration (see Fig. 5). For calculating the level of heat deposition it was assumed that it is inversely proportional to the measured ablation saturation depth [10; Fig. 4].

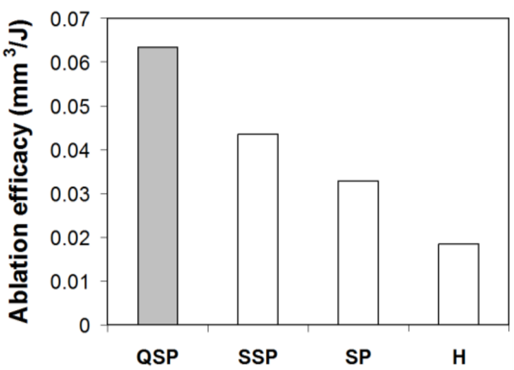


Fig. 3: Comparison of ablation efficacy in enamel for different Erbium laser modes as obtained from linear fits to the data shown in Fig. 2. QSP, SSP and SP are Fotona LightWalker's Er:YAG laser modes, and H is Biolase iPlus's Er,Cr:YSGG laser mode.

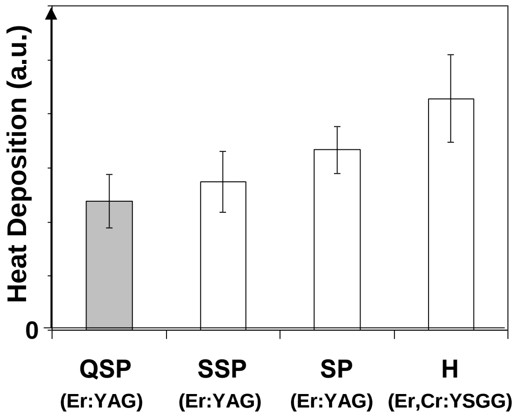


Fig. 4: Comparison of the level of heat deposition during hard tissue cutting for different Erbium laser modes as obtained from [10; Fig. 4]. QSP, SSP and SP are Fotona LightWalker's Er:YAG laser modes, and H is Biolase iPlus's Er,Cr:YSGG laser mode.

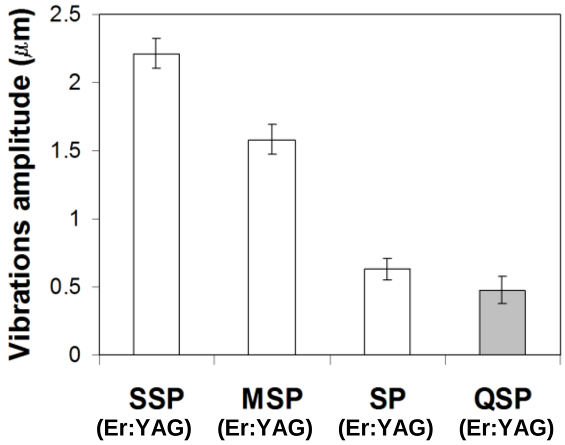


Fig. 5: Comparison of the level of vibrations during hard tissue laser cutting for different Erbium laser modes as obtained from [10; Fig. 10]. QSP, MSP, SSP and SP are Fotona LightWalker's Er:YAG laser modes.

Figure 6 shows the temporal sequence of an ablation cloud developing above an enamel surface during a QSP mode Er:YAG laser pulse, as measured with the Fastcam SA-Z 2100K-M-64GB camera (manufactured by Photron). The QSP mode pulse consists of an optimally modulated ASP structure consisting of five micro pulse "quanta" that follow each other at an optimal rate. Figures 6a and 6e show the instances in time immediately after two consecutive micro pulse quanta have been emitted within a QSP Er:YAG pulse. During the time in between the emission of individual micro pulse quanta (Figures 6b-6d), the ablation cloud of a preceding pulse quanta (Fig. 6a) has sufficient time to disperse, and therefore does not interfere with the radiation of a succeeding pulse quanta (Fig. 6e). This demonstrates that the ASP-powered QSP pulse mode is optimally adapted to the bio-photonic dynamics of laser-enamel interaction, thus avoiding the undesirable residual side effects of laser beam scattering and absorption in the debris cloud. This results not only in a higher ablation efficacy (see Figs. 2 and 3) but also in reduced heating (Fig. 4) and vibrations (Fig. 5), as shown above.

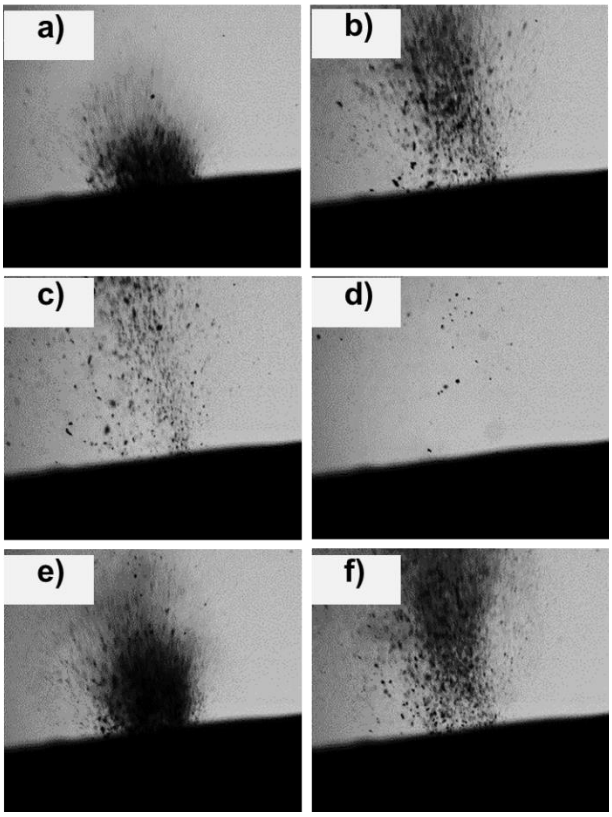


Fig. 6: Temporal sequence of an ablation cloud forming above an enamel surface during two consecutive pulse quanta within a QSP mode Er:YAG laser pulse. Figures 6a and 6e show the instances in time immediately after two consecutive micro pulse quanta within a QSP Er:YAG pulse have been emitted. During the time in between the emission of individual micro pulse quanta (Figs. 6b-6d), the ablation cloud of a preceding pulse quanta (Fig. 6a) has sufficient time to disperse, and therefore does not interfere with the radiation of the succeeding pulse quanta (Fig. 6e).

V. CONCLUSIONS

In conclusion, adaptive pulse structuring enabled by the latest ASP (Adaptive Structured Pulse) Er:YAG laser technology allows for optimization of Er:YAG laser performance with regard to critical requirements for minimally invasive laser dentistry.

In comparison to other tested Erbium modes, the ASP-powered Quantum Square Pulse (QSP) modality was shown to result in i) the fastest cutting in hard dental tissue; ii) the smallest amount of undesirable heat deposition; and iii) the lowest level of vibration.

DISCLOSURE

N. Lukac and M. Lukac are currently also employees of Fotona d.o.o.

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